

Final Technical Report for:

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Prof. M. G. Kivelson and Dr. K. K. Khurana (UCLA) are co-investigators on the Cluster Magnetometer Consortium (CMC) that provided the fluxgate magnetometers and associated mission support for the Cluster Mission. The CMC designated UCLA as the site with primary responsibility for the inter-calibration of data from the four spacecraft and the production of fully corrected data critical to achieving the mission objectives. UCLA will also participate in the analysis and interpretation of the data. The UCLA group here reports its excellent progress in developing fully intra-calibrated data for large portions of the mission and an excellent start in developing inter-calibrated data for selected time intervals, especially extended intervals in August, 2001 on which a workshop held at ESTEC in March, 2002 focused. In addition, some scientific investigations were initiated and results were reported at meetings.

Onboard Sensor Calibrations

One of the principal objectives of the Cluster Mission is to infer the spatial gradients of the magnetic field in the Earth's magnetosphere directly from first order differences in the field measurements at the four spacecraft. For relevant spacecraft separations, the differences are not large and small errors resulting from an inadequate knowledge of the orientations, zero levels and the scale factors of the magnetometer sensors can significantly affect the calculation of field gradients [Robert *et al.*, 1998a]. Khurana *et al.* [1996] have shown that twelve calibration parameters are required for each of the four spacecraft to infer the measured magnetic fields at each of the spacecraft correctly. Based on these ideas, we developed and successfully applied a two-step procedure for the full calibration of the spacecraft tetrad.

In the first step, referred to as intra-calibration, we used the fact that low frequency geophysical signals in the Earth's magnetosphere have a broadband character whereas miscalibrated despun data contain harmonic signal at the first and second harmonics of the spacecraft spin frequency. This procedure provides eight of the required twelve calibration parameters for each of the four magnetometers [Kepko *et al.*, 1996]. Next, we applied a technique that we refer to as inter-calibration. This procedure enabled us to determine the remaining calibration parameters by using the concept that $\nabla \cdot \mathbf{B}$ is zero everywhere and $\nabla \times \mathbf{B}$ is vanishingly small in many regions of the magnetosphere [Khurana *et al.*, 1996, 1998]. The technique works well although useful intercalibrations can be assured only for configurations of the spacecraft tetrad that span a spatial region close to that of a regular tetrahedron. We developed some new parameters describing the s/c locations, based on a principal axis analysis of the s/c distribution. These new parameters improve the characterization of the spatial distribution indicating if the coverage is appropriate for identifying the currents from the magnetic field.

Intra-calibration

This least squares technique improves the eight calibration parameters by iteration until the power of the coherent signal is minimized. The details of the technique were reported in *Kepko et al. [1996]*. The scheme was originally tested on ISEE and Galileo data sets and the results were extremely satisfactory. We used the technique on data from the four spinning spacecraft of the Cluster tetrad. Figure 1 shows a time series at full resolution (22 vec/s) from spacecraft 1 in GSM coordinates. The despun data obtained by using UCLA intracalibration procedure is virtually spin-tone free whereas despun data using ground calibrations shows significant spin tone.

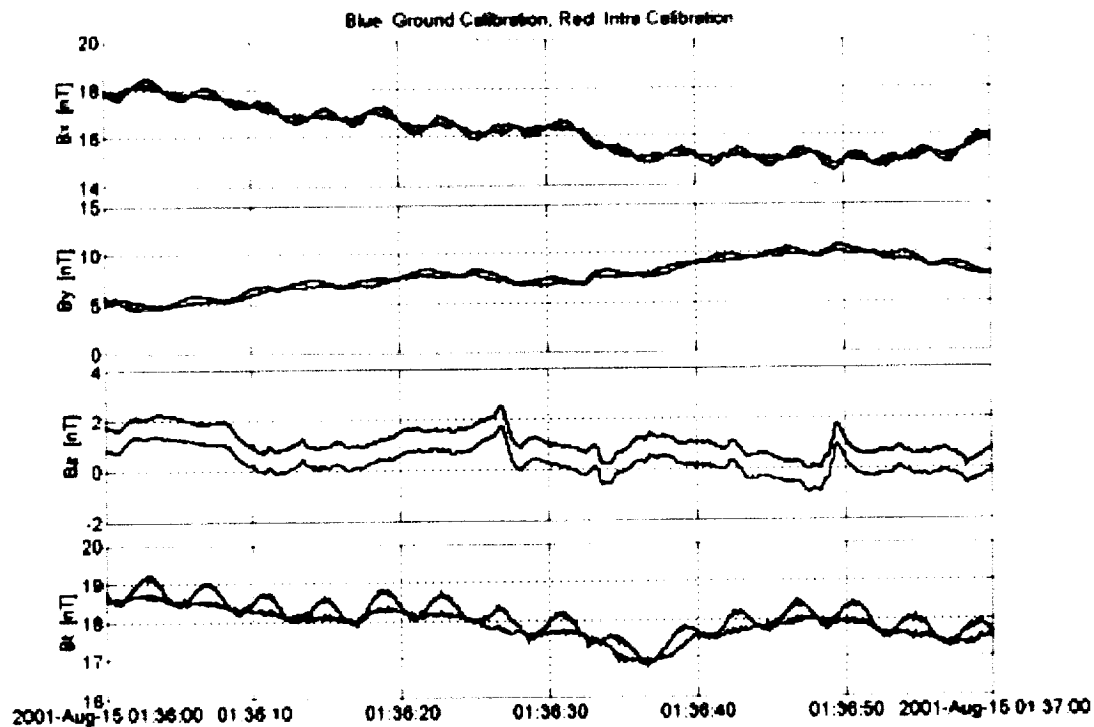


Figure 1. A high time resolution segment of Cluster data despun using ground (blue) and UCLA (red) calibration matrices. Notice that the intracalibration procedure has substantially reduced the spin tone and its harmonics in the despun data.

By using the UCLA intracalibration program routinely on the data, we found that the gains and alignments of the sensors have remained stable over the last year of operation. However, the offsets of the sensors show either cyclical or monotonic variations over the year. Figure 2 shows the zero-levels (offsets) for two of the sensors deduced over a period of six months using our intracalibration scheme. For comparison we also plot in the same figure the values of the offsets provided to us by the Braunschweig group. There is a good agreement between the two sets of offsets. The figure clearly shows that the offsets slowly drift and must be continuously monitored, especially during times when s/c temperature is changing rapidly.

Inter-calibration

Our approach to inter-calibration relies on the concept that $\nabla \cdot \mathbf{B}$ is zero everywhere in space and the electric current is vanishingly small in many regions of the magnetosphere. If the data have not been properly intercalibrated, they yield non-zero averages for $\nabla \cdot \mathbf{B}$ and $\nabla \times \mathbf{B}$ in those regions. Correct calibration parameters are determined by requiring that the final data set must yield values of $\nabla \cdot \mathbf{B}$ and $\nabla \times \mathbf{B}$ close to zero. The details of the technique were reported in *Khurana et al. [1996]*.

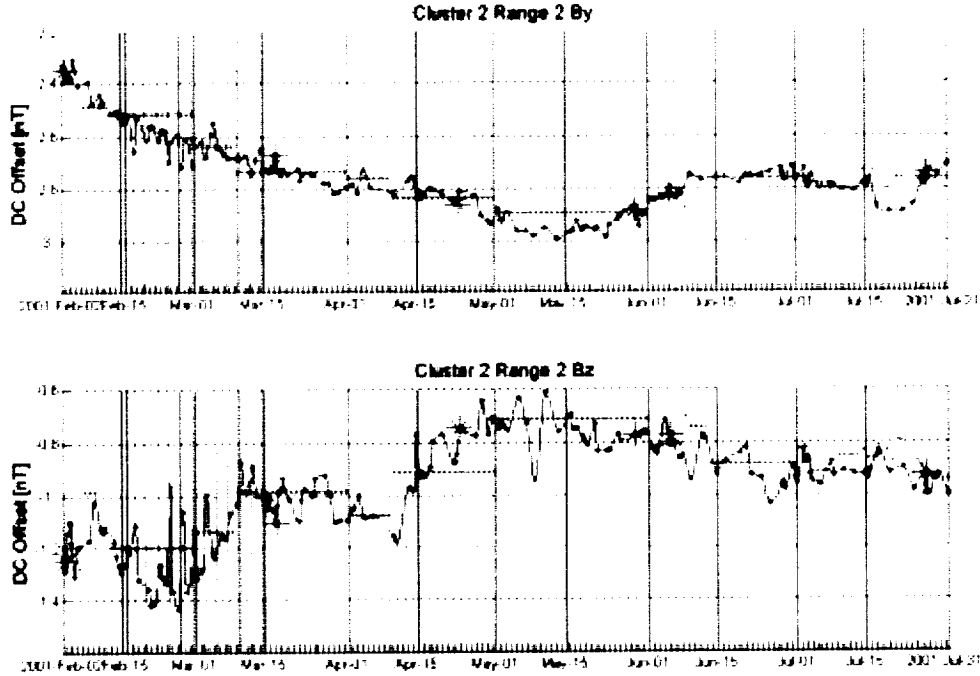


Figure 2. The offsets of the spin plane sensors (y and z) for spacecraft 2 in range 2. blue curve with red dots are the offsets obtained from the UCLA scheme. Brown horizontal line segments show the offsets obtained by the Braunschweig group. The offsets from both schemes show temporal drifts that should be monitored continuously. When the spacecraft passes through the Earth's shadow at some part of its orbit (marked by green vertical lines), the offsets of both sensors show cyclical variations.

For this scheme, we used the output from our intra-calibration technique. With a large data set from those regions of the magnetosphere where the electric current density is small, we were able to generate good calibration parameters.

Once the data were fully calibrated, we computed all nine spatial gradients of the magnetic field from the calibrated dataset. The computer program that we developed also outputs the instantaneous value of the electric current density (\mathbf{J}) and $\nabla \cdot \mathbf{B} / \mu_0$ in the volume enclosed by the tetrad. A data quality indicator, which characterizes the volume of the tetrahedron with vertices at the four spacecraft, is also generated. Figure 3 shows a sample output of this calculation for an interval when the spacecraft were located in the Earth's lobes (B_x large and noise-free). The values of $\nabla \cdot \mathbf{B} / \mu_0$ and $\nabla \times \mathbf{B} / \mu_0$ (units are

nA/m^2) are close to zero in the fully intercalibrated data (blue traces lower plot), as desired. However, data that have not been intercalibrated (red traces with spin tones in lower plot) fluctuate about values of a few tenths of a nA/m^2 for $\nabla \cdot \mathbf{B} / \mu_0$ and 0.8 nA/m^2 for $\nabla \times \mathbf{B} / \mu_0$.

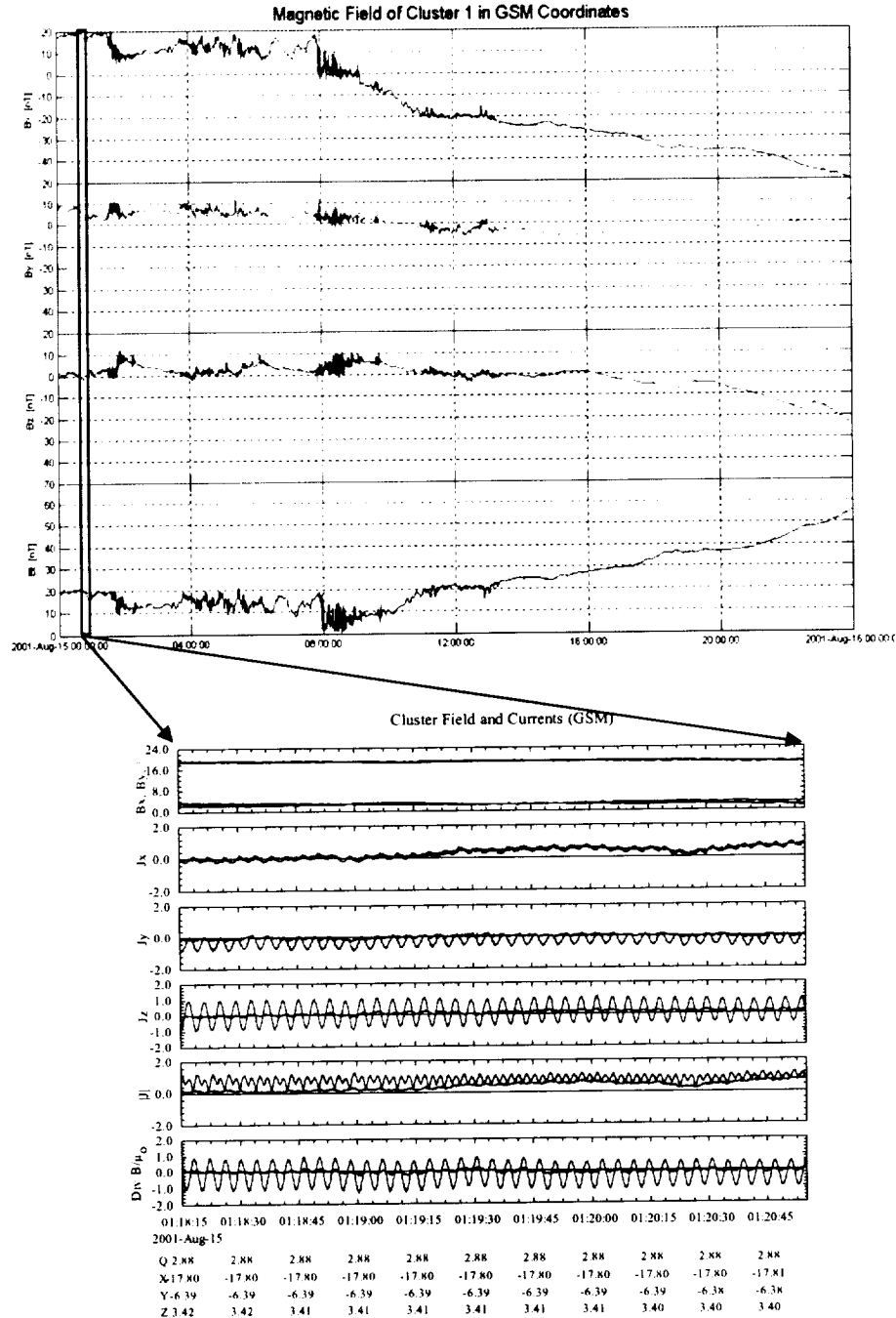


Figure 3. \mathbf{B} at spacecraft 1 in nT (panel 1 of lower plot), current density (panels 2-5 of lower plot) and $\nabla \cdot \mathbf{B} / \mu_0$ (panel 6 of lower plot) computed in nA/m^2 using our intercalibration procedure (blue traces) and without using our calibration procedure (red traces) for a 2 minute interval. The top graph shows the measured magnetic field (nT) at spacecraft 1 for a full day on August 15, 2001.

For use in scientific analysis, we created data sets that resolved the current density into its field-aligned and field-normal components.

The influence of eclipses on sensor offsets

Analysis of the offsets of the sensors over a period of ~ 1 year showed that some of the magnetometer sensors experience abrupt changes in their zero levels when the spacecraft are in the Earth's shadow. Figure 2 shows the effect of solar eclipses on the measured sensor offsets. Thus, for Cluster 2, for sensor z in range 2 (lower panel), each time the spacecraft is in eclipse (marked by green vertical lines), the zero level of the sensor decreases anywhere between 0.1 nT to 0.3 nT. It is our understanding that two factors contribute to the changes in the offsets. The probable reason is that when the spacecraft are in eclipse, the sensor temperatures drop, causing sensor volumes to change slightly. Such volume changes then lead to changes in measured field and therefore appear as sensor offsets. Another feature of operation that may contribute is that onboard sensor heaters are turned on to keep the sensor warm when the spacecraft is in eclipse. The sensor heaters generate small but appreciable magnetic fields that mimic changes in the zero levels of the sensors. During the reporting period, we began to work on the problem of optimizing calibration during times of changing environment. The results of the calibration studies were reported to the FGM Principal Investigator, Dr. Andre Balogh, in several (unpublished) reports of which we attach representative examples.

Scientific Analysis

We began to exploit the magnetic field data for its scientific potential. Some initial results were obtained both on signals that we believe to be the signature of bursty reconnection poleward of the cusp in the high latitude lobe, and on signatures of dynamical processes in the magnetotail plasma sheet.

The exploration of the cusp region

During the first half of 2001, the Cluster II orbit was optimized for the investigation of encounters with the high-altitude polar cusp. We identified several events where the spacecraft tetrahedron repeatedly encountered flux transfer event (FTE) type structures. Figure 4 shows an example of the passages of several such structures. This work was reported at the Fall AGU meeting in San Francisco [Thompson *et al.*, 2001].

scheme described above, we calculated the electric current flowing through the magnetotail current sheet. We found that the current sheet is highly filamented, extremely dynamic and is rarely in magnetostatic equilibrium. During this period, several magnetospheric substorms were detected in ground observations. We initiated a study of the associated changes in the configuration of the magnetotail current sheet and related them to plasma flow observations.

The filamentation of the current sheet is of interest not only for understanding geomagnetic activity, but also for understanding the degree to which the structure of the current sheet can ever mimic the equilibrium Harris current sheet so beloved of theorists. In order to test whether the Harris current sheet model is ever relevant, we began to investigate the relation implied by the mathematical model. With $B_x = B_o \tanh(z/\lambda)$, it follows that $j_y = (B_o / \mu_o \lambda) \text{sech}^2(z/\lambda)$. This means that $j_y = (B_o / \mu_o \lambda)(1 - \tanh^2(z/\lambda))$ or $j_y = (B_o / \mu_o \lambda)[1 - (B/B_o)^2]$.

We started testing the statistical validity of this relationship which implies a linear relation between j_y and B_x^2 with a negative slope. Initial evidence showed considerable scatter but an overall relation to the model, an area that will absorb our attention in the coming year.

Cluster Studies of Magnetospheric Substorms

The Cluster mission with its identical instruments on multiple spacecraft provides a unique opportunity to advance the study of the processes responsible for geomagnetic activity, particularly the cause of the magnetospheric substorm. Today, one of the outstanding problems in Space Physics is to explain the process that initiates the substorm expansion phase [Spence, 1996]. The standard paradigm posits that it is localized, transient magnetic reconnection somewhere tailward of 15 Re [Baker et al., 1996]. An alternative hypothesis is that it caused by instability of the cross-tail current Earthward of this distance [Lui, 1996]. In our interpretation of the magnetotail passes, we have initiated studies of the substorms that occur during the interval of a plasmasheet crossing, and we find there are numerous cases worthy of attention.

Figure 5 shows magnetometer data for a substorm expansion observed at about 0130 LT on August 15, 2001 at about 18 R_E down the tail. This expansion had multiple onsets both before and after effects were observed at the Cluster location. Most evident in these data is the signature of field-aligned currents seen after 0132 in the B_y component. More subtle, but no less important is the relative timing of the arrival of these effects at the four spacecraft. Taking into account their locations we were able to show that the disturbance represents a thickening of the plasma sheet propagating from midnight towards dawn engulfing the four spacecraft. The leading edge of this front was oriented at a steep angle to the normal boundary. Subsequently the boundary oscillated vertically about the spacecraft causing a nesting of the B_x contours centered on 0140 UT. An examination of the time delays showed that the current sheet was moving up and down with velocities of order 100 km/s. Not evident with this expanded scale is the fact that the tail current sheet was not oriented in GSM coordinates as one would expect this close to the Earth, but was

References

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Thompson, S.M., M.G. Kivelson, K.K. Khurana, and A. Balogh, Cluster: Quasi-periodic impulsive signatures on the dayside magnetopause, *Eos, Trans. AGU*, 82 (Fall Meet. Suppl.), SM22A-0789, 2001.

Williams, D.J., and T.A. Fritz, An energetic particle perspective of the magnetopause., *J. Geophys. Res*, 84, 6385-96, 1979.

Presentations during the reporting period

Thompson, S.M., M.G. Kivelson, K.K. Khurana, and A. Balogh, Cluster: Quasi-periodic impulsive signatures on the dayside magnetopause, *Eos, Trans. AGU*, 82(47), Fall Meet. Suppl., Abstract SM22A-0789, 2001.

R.L. McPherron, M.G. Kivelson, A. Balogh and others, Cluster Observations of Substorms on August 15, 2001, Cluster Workshop, ESTEC, Netherlands, March 2001.

Sample Calibration Reports during the reporting period (copies attached).

Volwerk, M., K. Khurana, and M. Kivelson, Cluster Calibration Progress Report (2001-04-24)

Kivelson, M. G. and K. K. Khurana, Progress Report on UCLA Cluster Calibration – October 4, 2001

**Progress Report on UCLA Cluster Calibration –
October 4, 2001**

M. G. Kivelson, K. K. Khurana
*who acknowledge the able contributions of
Hannes Schwarzl, Martin Volwerk, and Baptiste Carvello*

- UCLA is responsible for intercalibration of the magnetometers on the four Cluster 2 spacecraft. In our first intercalibration attempts, we used the calibration files provided through
<http://www.cluster.rl.ac.uk/FGM/>
- We used several different approaches to the effort, but we were unsuccessful in obtaining intercalibrations that reduced the components of the curl of the field to values appropriate in regions away from boundaries or active regions.

1

Identification of drifting offsets

- This led us to investigate the possibility that offsets might be changing in response to thermal changes of the spacecraft. Therefore, we have undertaken a systematic analysis of the offsets of the sensors in the spin plane.
- We present here evidence for small drifts, sufficient to account for our problems in intercalibration.
- We show that the drift in the offsets results at least partially from thermal effects.

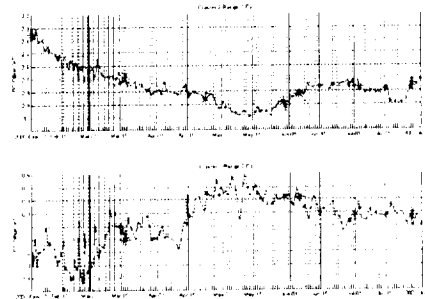
2

The zero levels of the two spin plane sensors for each range & for each spacecraft were obtained as follows

- Step 1. Generate spin-averaged data using zero offsets in the calibration file.
- Step 2. Carry out a running average over 80 points (320 sec). Shift by 40 points or 160 s between averaging intervals.
- Step 3. Retain only quiet intervals as selected by eye.
- Step 4. Average the remaining quiet intervals over 6 hours (or over the <6 hour interval in which the instrument range does not change) to obtain offset. *The points obtained this way are plotted as red dots in the plots of offsets vs. time that follow.*

3

Cluster 2, range 2. Zero levels vs. time



Red dots show long-term averages of spin plane sensors
•Other features of the plot will be explained below.

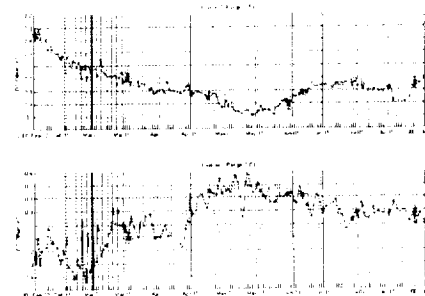
4

Obtaining zero levels of the two spin plane sensors for each range - continued

- Step 5. Use a piecewise cubic Hermite interpolation as implemented in MATLAB 6 (function: pchip) to join the points. Details are given below.
 - *The results of the interpolations are plotted as blue curves in the plots that follow.*
- Step 6: From the interpolation, daily values for the offsets are obtained by using the interpolated values at noon.

5

Cluster 2, range 2. Zero levels vs. time



•The blue curves are obtained by interpolation.

The interpolation procedure used for offsets

- The derivatives of the curves fitted in the MATLAB program are obtained in the following way:
 - If the sign of the derivative changes at a point or if the derivative is zero at a point, the derivative is set to zero.
 - The derivative is set to the weighted average if its sign does not change.
 - The first derivative is always continuous.
- References provided by MATLAB:
 - [1] Fritsch, F. N. and R. E. Carlson, "Monotone Piecewise Cubic Interpolation," SIAM J. Numerical Analysis, Vol. 17, 1980, pp 238-246
 - [2] Kahaner, David, Cleve Moler, Stephen Nash, "Numerical Methods and Software", Prentice Hall, 1988

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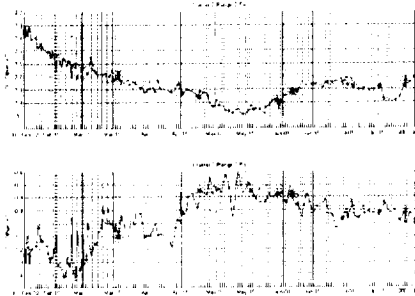
Comparison with the Kepko *et al.* calibration results

- For some specific time intervals, the technique of Kepko *et al.** was implemented to obtain the full calibration matrix.
- This analysis gives the values for offsets plotted as black stars *. They are in excellent agreement with the offsets obtained from the averaging procedure described above.
 - The interpolated values were replaced by the values represented by the stars when the latter were available.

* Kepko, E. L., K. K. Khurana, and M. G. Kivelson, Accurate determination of magnetic field gradients from four point vector measurements. 1. Use of natural constraints on vector data obtained from a single spinning spacecraft. *IEEE Transactions on Magnetics*, 32, 377, 1996.

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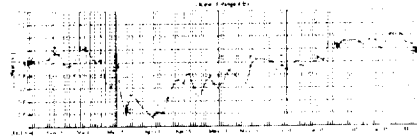
Cluster 2, range 2 zero levels vs. time



Stars (*) are offsets from the Kepko *et al.* method

Comparison of offsets

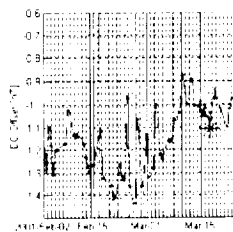
- Also plotted are the offsets provided by the FGM website <http://www.cluster.rl.ac.uk/FGM/>
- They are shown as orange bars.
- New offsets are typically provided every few weeks.
- Differences are in the tenths of nT range.



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Effect of varying temperature

- Green lines on the plots show intervals in which Cluster went into eclipse.
- Offsets in ranges 2 & 3 (which often bracket eclipses) show marked and systematic changes in comparisons between pre- and post- eclipse values suggesting sensitivity to changing temperatures.
- Example is for z-sensor offset, Cluster 2 range 2.

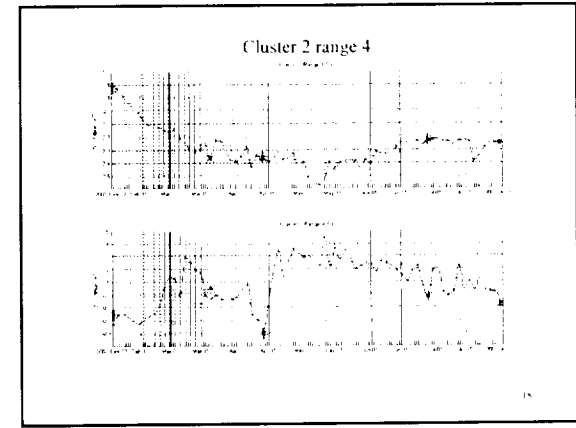
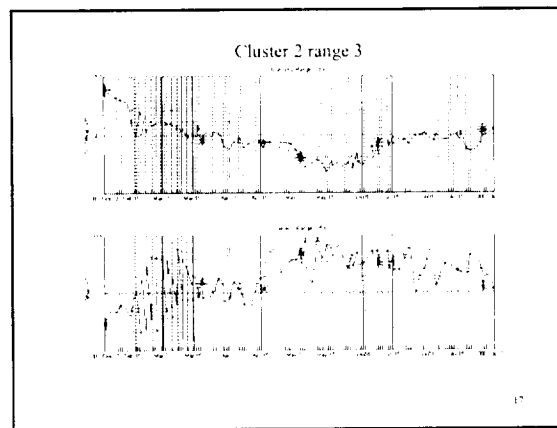
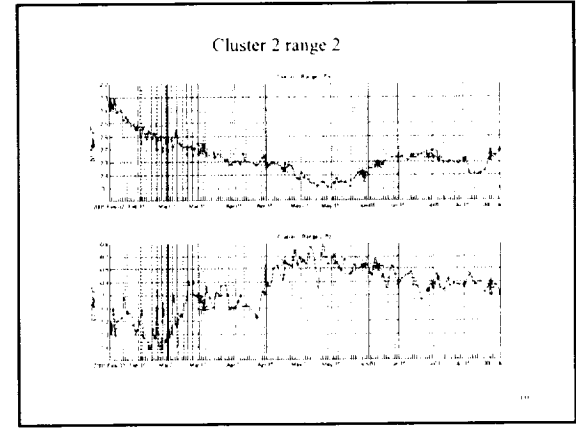
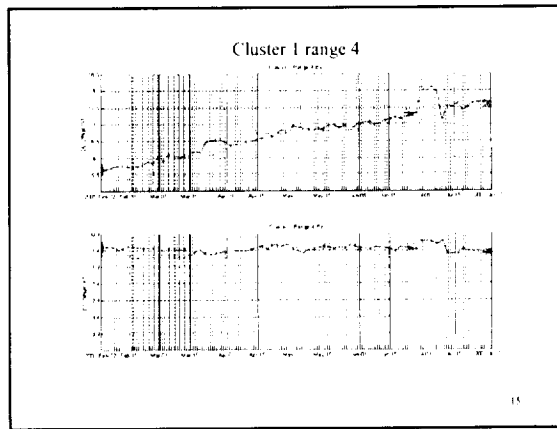
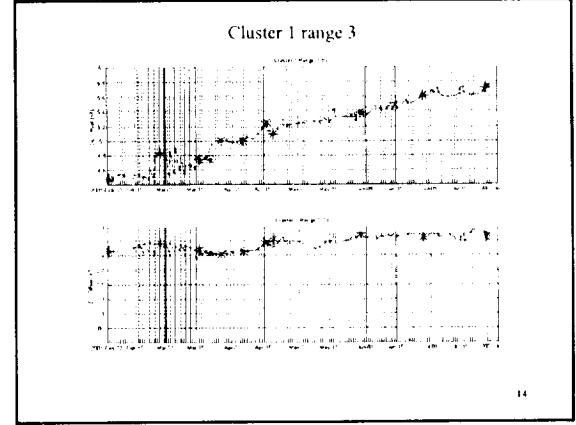
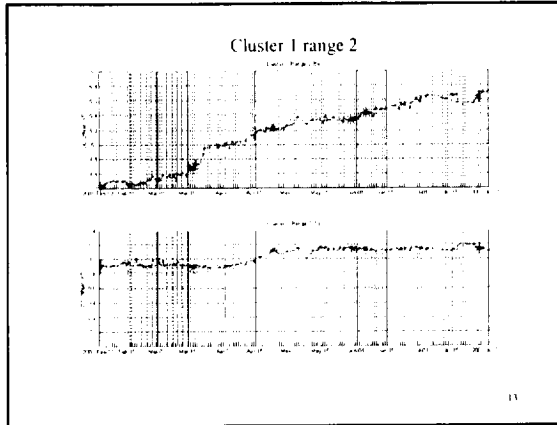


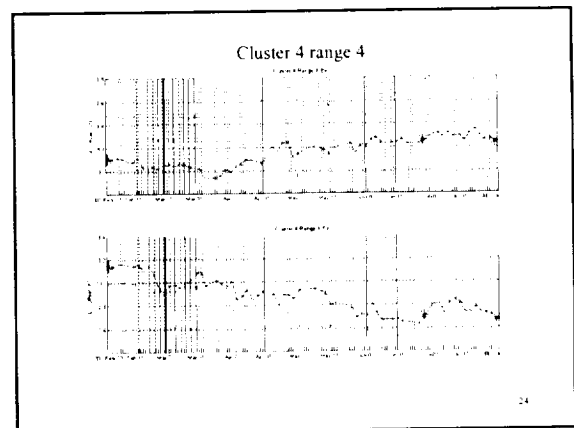
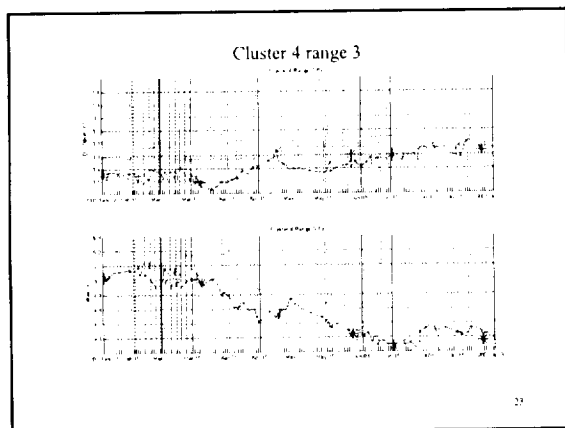
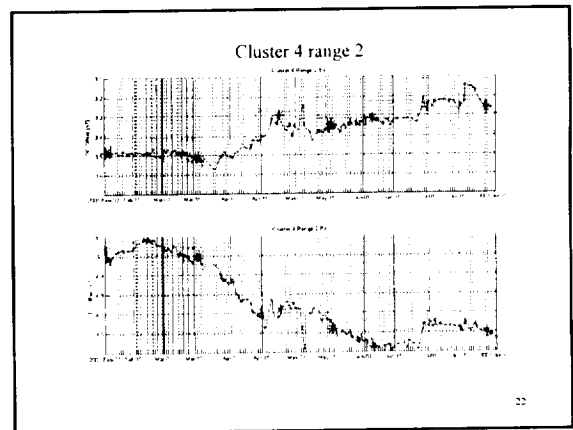
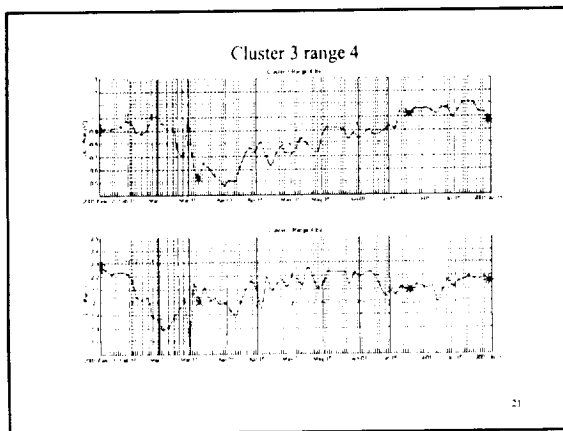
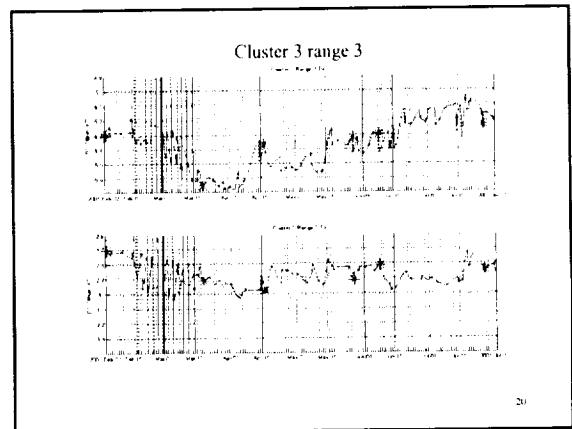
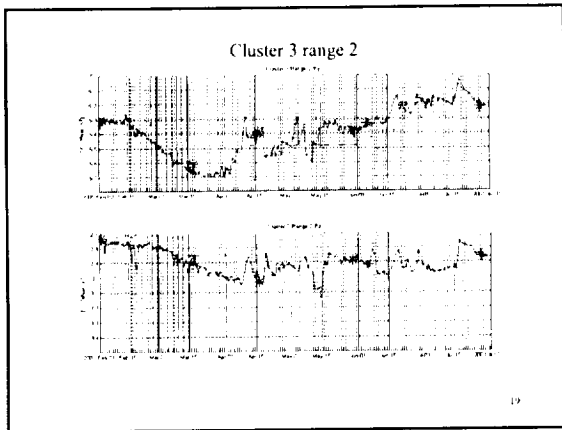
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Summary plots

- The plots that follow show the drifts of offsets in separate ranges for all four spacecraft.
- Variations and differences between initial offsets and new offsets are of order tenths of nT.

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Tests of the UCLA calibration

- The next set of plots provides evidence of the quality of the calibration performed. Averaged amplitude spectra for quiet intervals in the different ranges of the FGM were obtained in the following manner:

Step 1. Select intervals of data with low levels of natural fluctuations for the different sensors and the different ranges.

Step 2. Using a window length of 2048 points, obtain Fourier spectrum using a Hanning filter. Shift by 1024 points between successive spectra.

Step 3. Average the spectra within a given range.

25

Comparison plots follow

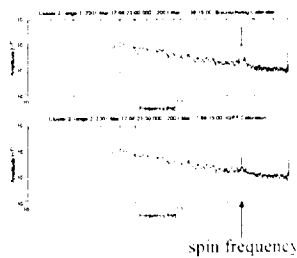
- The averaged spectra are plotted for data calibrated with the original calibration matrices and with the improved calibration matrices. In both cases, small amplitude residual power remains at the spin frequency, but the new calibration reduces the power at the spin frequency by typically an order of magnitude.

-- For purposes of comparison, it is noted that the digital resolution of the different ranges is as follows:

- Range 2 $\rightarrow 0.007813$ nT
- Range 3 $\rightarrow 0.03125$ nT
- Range 4 $\rightarrow 0.125$ nT

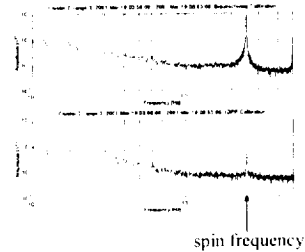
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Cluster 2 range 2



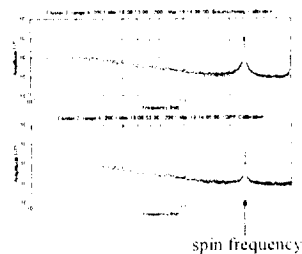
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Cluster 2 range 3



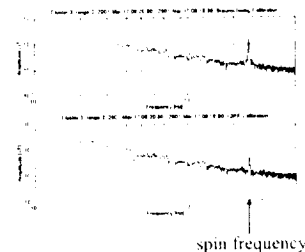
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Cluster 2 range 4

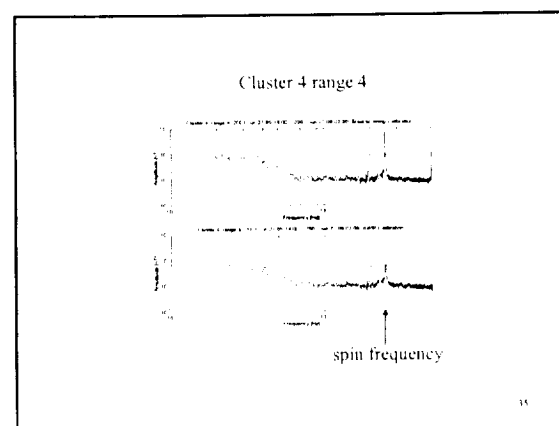
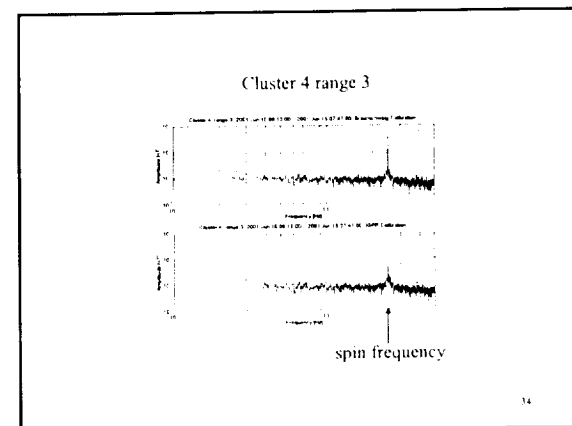
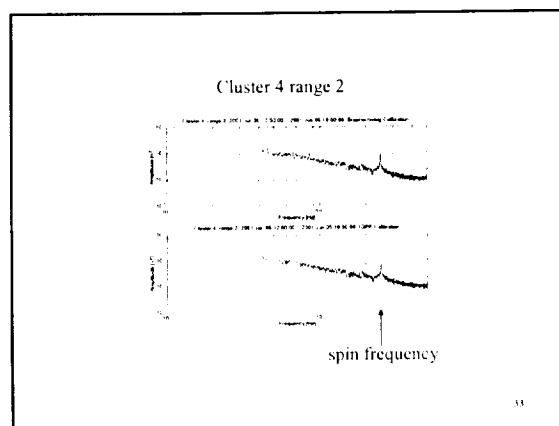
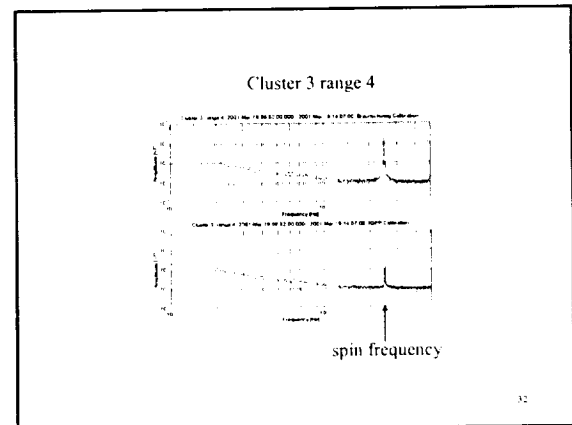
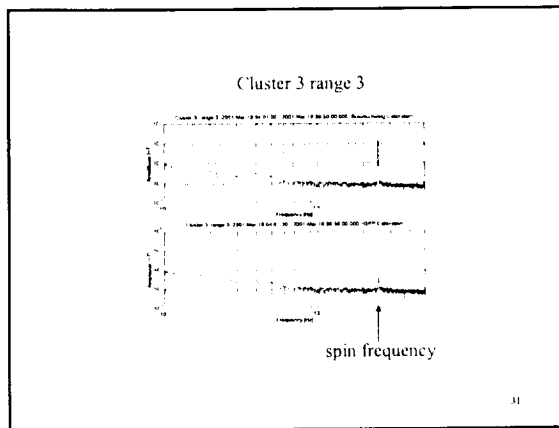


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Cluster 3 range 2



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Examples of processed data

- Two plots of data processed with the initial and improved calibration matrices are provided.
- The plots include a "good case" in which the new offsets are close to the initial offsets and spin tone is not apparent in either trace and a "problematic case" in which they are substantially different and spin tone remains when the original calibration matrix is used.

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Cluster Calibration Progress Report (2001-04-24)

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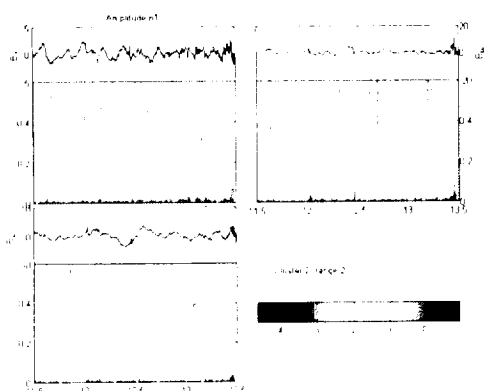
We have successfully intra-calibrated ranges 2 (± 64 nT), 3 (± 256 nT) and 4 (± 1024 nT) for all 4 Cluster spacecraft. The main day used for performing the calibration was February 2nd, 2001, however, data from February 4th, 7th and 14th were also used.

It is the purpose of this document to show how good the calibration is and how stable. Therefore we shall show dynamic spectra of the data and concentrate on the frequency range in which the 1st and 2nd harmonics (0.25 and 0.5 Hz) of the spin period (~ 4 seconds) are. As we will be working mainly in GSE coordinates, we will use this coordinate system as input for our spectral analysis tool (Bx, By, Bz), however, the tool itself will calculate a dynamic field aligned coordinate system (transverse components Bv, Bp, aligned component B μ). To decrease the number of points in the spectral analysis we have averaged the data over 0.25 second intervals.

Dynamic spectra of 2 hours of data

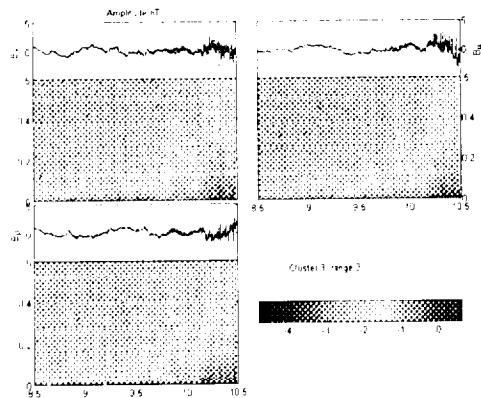
The following three figures show dynamic spectra of the data of February 2nd (range 2 and 3) and February 4th (range 4). The dynamic spectrum has been calculated over 256 points (~ 100 seconds) with shift over 128 point (~ 50 seconds). There has been no averaging over spectral harmonics. The data are taken from the start of the range change, i.e. we start off with the highest magnitude in magnetic field strength.

Range 2



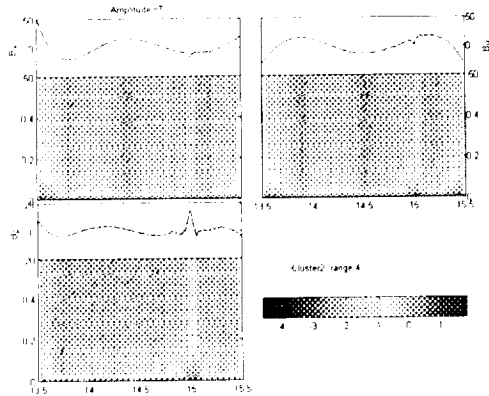
It is clear from the dynamic spectrum that there is still a small spin tone at the first harmonic present in the data. This might be improved when we use a new data set for the calibration. This will be done further down, when we start comparing the mutual angles of the sensors of the spacecraft. At the moment there is a residual of ~ 0.05 nT in the data.

Range 3



The calibration for range 3 is much better than that of range 2. Clearly there might still be a very small signal left of the spin tone at 0.25 Hz in very patchy regions, at very small amplitude

Range 4



Range 4 has been very well calibrated. There is no sign of any spin tones in the dynamic spectra.

How stable is the calibration?

We have performed the calibration for one day, February 2nd (or 4th for range 4). Baptiste has performed the calibration for range 3 for data from February 7th. Below we will show a table in which we compare the components of both calibrations.

The columns as they appear in the tables below are in the same format as the official cluster calibration files used in the FGM data flow system

The most important differences are in the offsets S#_01 (spin axis), S#_02 and S#_03 (transverse components), from which we see that the offset can shift over 0.05 nT over several days. (Joe is making a calibration for a date later in February, but it was not finished yet by the time I send this).

Rumba	Feb 2 nd	Feb 7 th	difference	Salsa	Feb 2 nd	Feb 7 th	difference
S1_01	-2.48239	-2.481	-0.00139	S2_01	0.36599	0.367	-0.00101
S1_02	4.472435	4.531	-0.05857	S2_02	-2.31246	-2.368	0.055543
S1_03	0.978222	0.944	0.034222	S2_03	-1.26613	-1.196	-0.07013
S1_11	1.0338	1.033797	3.2E-06	S2_11	1.025659	1.025656	2.8E-06
S1_12	0.007797	0.008083	-0.00029	S2_12	-0.00265	-0.00264	-1E-05

S1_13	0.012171	0.011917	0.000254	S2_13	0.005958	0.00595	8E-06
S1_21	0.003705	0.003724	-1.9E-05	S2_21	-0.00987	-0.00964	-0.00023
S1_22	1.033701	1.033712	-1.1E-05	S2_22	1.031637	1.031659	-2.1E-05
S1_23	-0.00786	-0.00793	6.45E-05	S2_23	-0.01127	-0.0114	0.000123
S1_31	0.006437	0.00627	0.000167	S2_31	-0.00053	-0.00089	0.000356
S1_32	-0.0002	-0.0002	-5E-07	S2_32	-0.0002	-0.0002	-9E-07
S1_33	1.017775	1.01777	4.5E-06	S2_33	1.038312	1.03831	1.7E-06

Samba	Feb 2 nd	Feb 7 th	difference	Tango	Feb 2 nd	Feb 7 th	difference
S3_01	-1.77536	-1.774	-0.00136	S4_01	-13.295	-13.295	-3.4E-05
S3_02	-5.30423	-5.257	-0.04723	S4_02	-3.43444	-3.464	0.02956
S3_03	-2.70442	-2.711	0.006578	S4_03	5.01836	5.057	-0.03864
S3_11	1.023753	1.023758	-4.3E-06	S4_11	1.023445	1.023445	4E-07
S3_12	0.01444	0.014361	7.9E-05	S4_12	-2.5E-05	2.77E-05	-5.3E-05
S3_13	-0.00324	-0.00327	3.57E-05	S4_13	0.006114	0.00613	-1.5E-05
S3_21	-0.00847	-0.00814	-0.00033	S4_21	-0.0082	-0.00865	0.000446
S3_22	1.019868	1.019774	9.38E-05	S4_22	1.060605	1.06064	-3.6E-05
S3_23	-0.01295	-0.01278	-0.00017	S4_23	-0.02096	-0.02094	-1.6E-05
S3_31	-0.00374	-0.00367	-6.3E-05	S4_31	0.002464	0.002442	2.21E-05
S3_32	-0.00027	-0.00027	-1.2E-06	S4_32	-0.00038	-0.00038	-1E-07
S3_33	1.037064	1.037064	3E-07	S4_33	1.033801	1.033801	2E-07

What do we know about the sensor angles on the spacecraft for different ranges

The intra-calibration code calculates the mutual angles between the different sensors on the spacecraft.

Rumba			
range	ang12	ang23	ang13
4	90.541726	90.616352	88.987505
3	90.460042	90.645666	88.954683
2	90.445948	90.662580	88.866086

	dThetaX	dThetaY	dThetaZ	dPhiY
4	0.3605	-0.2215	0.7592	0.5403
3	0.3568	-0.2081	0.8129	0.4588
2	0.3622	-0.1752	0.9096	0.4449

Salsa			
range	ang12	ang23	ang13
4	90.644649	89.318212	89.717011
3	90.630445	89.304787	89.702617
2	90.627265	89.292137	89.492069

	dThetaX	dThetaY	dThetaZ	dPhiY
4	-0.0430	0.5371	0.3582	0.6443

3	-0.0297	0.5514	0.3588	0.6302
2	0.1711	0.5514	0.3730	0.6289

Samba

range	ang12	ang23	ang13	
4	90.682670	90.327644	90.381444	
3	90.731122	90.332275	90.377713	
2	90.716786	90.344892	90.452828	
	dThetaX	dThetaY	dThetaZ	dPhiY
4	-0.2136	0.4818	0.8286	0.6809
3	-0.2092	0.4767	0.8285	0.7294
2	-0.2848	0.4669	0.8311	0.7145

Tango

range	ang12	ang23	ang13	
4	91.191483	89.561833	89.492637	
3	91.178084	89.549223	89.523374	
2	91.178644	89.642441	89.573809	
	dThetaX	dThetaY	dThetaZ	dPhiY
4	0.1511	0.4459	0.3563	1.1927
3	0.1378	0.4564	0.3388	1.1792
2	0.0801	0.3668	0.3461	1.1792

One sees that the angles are very similar for the different ranges, with significantly large differences in two cases, Salsa range 2 and Tango range 2, and quite possibly Samba range 2. In order to check the angles for range 2 we have done a new intra-calibration for February 14th, for Salsa and Tango. We obtained the following result:

Salsa:

dThetaX	dThetaY	dThetaZ	dPhiY
-0.0946	0.4614	0.3657	0.6275

Tango:

dThetaX	dThetaY	dThetaZ	dPhiY
0.1052	0.4529	0.3402	1.1878

This shows that further intra-calibration will probably lead to angles that will differ no more than a few times 10^{-2} .

Another checkpoint that is found now is the offsets of these two spacecraft from this latest calibration:

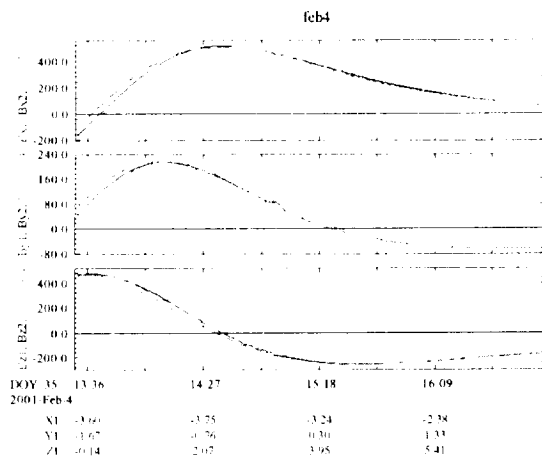
	Feb 2 nd	Feb 14 th		Feb 2 nd	Feb 14 th
S2_01	0.36599	0.297	S4_01	-13.295	-13.313

S2_02	-2.31246	-2.545	S4_02	-3.43444	-3.484
S2_03	-1.26613	-1.271	S4_03	5.01836	5.027

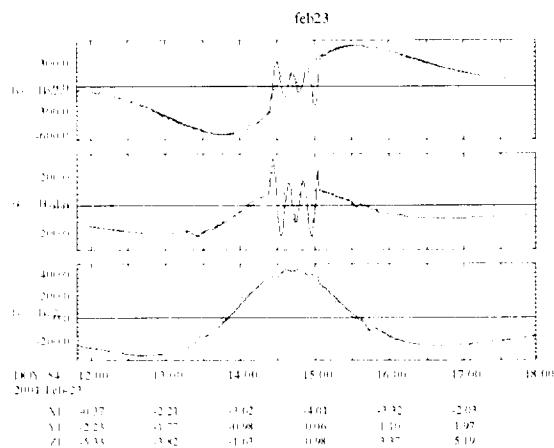
There are small changes in the offsets. Notable is the change in S2_01, which is not a variable that we are solving for, but can be changed slightly in our processing.

Inter-calibration of the four spacecraft

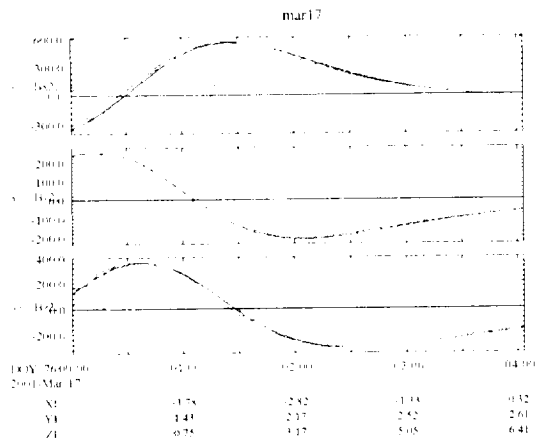
We now take three perigee passes in range 4 (1024 nT), on days February 4th, February 23rd and March 17th. This gives a good range in magnetic field values as can be seen from the data figures.



These plots are in GSE coordinates. To perform the inter-calibration we have not used all of these three passes, but have eliminated the regions that are clearly influenced by currents. These show up as disturbances in these one minute averaged data.



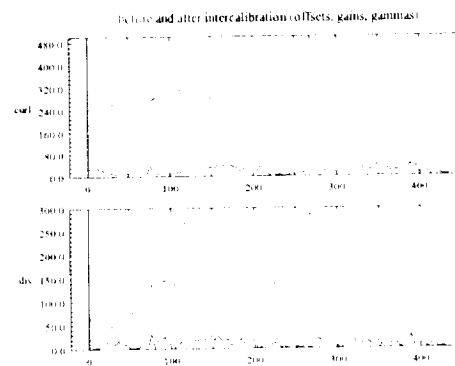
At perigee on February 23rd the spacecraft were in eclips. That accounts for the strange behaviour of the data in the middle of this figure, as the spacecraft spin rate is not accurately recorded.



For the inter-calibration we have solved for two different sets of parameters. First we have solved for the relative offsets, gains and the angle around the rotation axis (gamma). Then we solved for all parameters, which include the relative angles around the x (alpha) and y (beta) axes.

The result for the first run of the inter-calibration program in Tabular and graphical form:

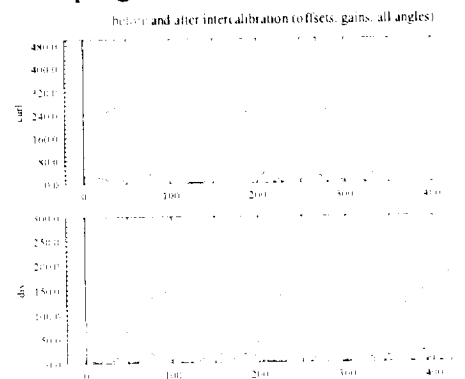
	spacecraft		
	1	2	3
alpha	0.0000	0.0000	0.0000
beta	0.0000	0.0000	0.0000
gamma	0.8559	0.1650	0.1431
x,y gain	0.0014	0.0063	-0.0036
z gain	-0.0017	0.0014	-0.0080
offset	1.7831	-10.1123	4.3513
divb	curlb	both	
11.9455	17.7866	21.4257	



These values are all with respect to the mother spacecraft Rumba. It is clear that the curl and div has been greatly reduced by this procedure. Flying the spacecraft through the Tsyganenko 96 magnetospheric model, the values for curl and div B are similar to those of the blue lines in the figure.

For results for the second run of the inter-calibration program in the same format

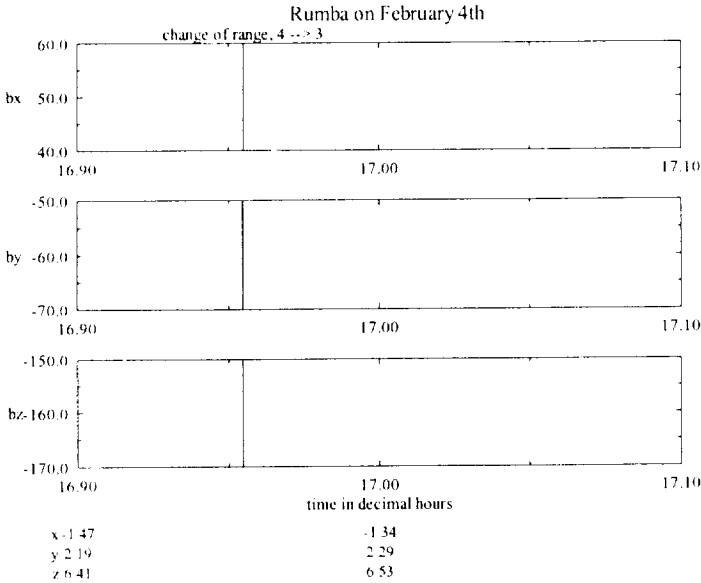
	spacecraft		
	1	2	3
alpha	-0.2094	-0.0933	-0.2567
beta	-0.2466	-0.1998	-0.3850
gamma	1.0595	0.2919	0.3005
x,y gain	0.0044	0.0090	0.0012
z gain	-0.0033	-0.0005	-0.0106
offset	2.6728	-9.5375	5.3388
divb	curlb	both	
9.1991	16.8756	19.2201	



This shows that there is enough information in the three perigee passes to come to a complete inter-calibration.

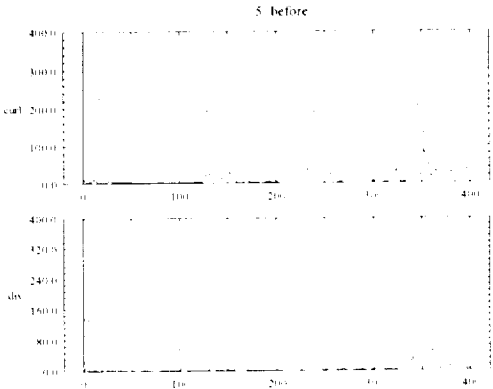
For the next range (3), there is a problem with range if we only take into account three passes, therefore we use range 3 measurements from the following dates: February 4th, 13th, 23rd, March 16th and 17th. This gives us a good range in magnetic field strength and in absolute value of the different components.

In addition, we have added a 2.86 nT offset to the Bz component of Rumba, which is the jump that occurs when going from range 4 to range 3.



The result of inter-calibrating range 3 is the following:

	spacecraft		
	1	2	3
alpha	-0.2094	-0.0933	-0.2567
beta	-0.2466	-0.1998	-0.3850
gamma	1.0595	0.2919	0.3005
x,y gain	0.0044	0.0090	0.0012
z gain	-0.0033	-0.0005	-0.0106
offset	2.6728	-9.5375	5.3388
divb	curlb	both	
9.1991	16.8756	19.2201	



Notice that these results are very similar to the results above for range 4.

Our goal was that after inter-calibration, and after adding an z-offset to spacecraft Rumba that we would recover data sets for the three daughter spacecraft which would not show any sign of the jump shown in the above figure. Unfortunately, we have not totally reached this goal. After performing the inter-calibration rotations and offsets and gains, we ended up, for Salsa, with no jump in B_z (which is good) but there appeared a jump in B_y (which is not good), albeit that the jump was very much smaller. This might be caused by the fact that our inter-calibration is not optimal for implementation into the FGM software calibration files. We continue working on this.